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APPLICATION OF MUON SPIN RELAXATION EXPERIMENT TO THE VORTEX DYNAMICS OF HIGH TEMPERATURE SUPERCONDUCTORS

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We discuss the potential use of muon spin relaxation (μSR) technique to investigate the dynamics of the magnetic flux lines (vortices) in the mixed state superconductors. We argue that with the high critical temperature and large anisotropy found in some high temperature superconductors, one can use μSR to observe both static and dynamic behaviors of vortices. Recent experiments on $Bi_2Sr_2CaCu_2O_8$ are interpreted in this context.

In high temperature superconductors, it is well known that magnetic flux lines (vortices) are mobile at temperatures close to the critical temperature (T_c) due to thermal fluctuations.[1] However, the nature of the low temperature vortex state remains to be clarified. The difficulty lies mainly in the techniques employed in investigating the dynamics at low temperature. All the previous methods relied on measuring the response of vortices under external perturbation or non equilibrium configuration,[2] and it is unclear if any of these methods can really be used to study the low temperature regimes where vortices are not very mobile and responsive. (One exception is the Bitter pattern decoration experiment. However, this method is limited to very low external field, and the measurement is done only on the surface of the sample.)

The muon spin relaxation (μSR) experiment, on the other hand, is a technique that is largely non perturbative to the system, and explores the bulk. However, due to the relatively short lifetime of muons (about $2.2\,\mu s$), it has not been a very effective tool in studying the vortex motion. Roughly, vortices look "frozen" within such time scales in ordinary superconductors. In fact, this has been used to advantage in measuring the penetration length λ of these materials, as well as high T_c systems without much vortex motion.[4]

In certain high T_c materials (such as $Bi_2Sr_2CaCu_2O_8$), however, the vortices seem to be strongly mobile,[5] clearly due to the higher anisotropy (they have almost layered structures), and μSR may be capable of investigating their *dynamic* behavior. Let us consider the necessary criterion for this to be possible.

The most important quantity in a μSR measurement is the second moment of the field distribution[6] $\langle\Delta B^2\rangle = \langle(B - \langle B\rangle)^2\rangle$ where $\langle\cdots\rangle$ stands for the spatial *and time* average over the muons' lifetimes. In the case of static (or near static) vortices, this average is same as just the spatial average. However, in the case of very mobile vortices, $\langle\Delta B^2\rangle$ is reduced due to the time averaging process. One can see this by simply considering the peak (i.e. the highest) time averaged field in the system a muon can observe. When the vortices are frozen, it is simply the field at a vortex core, whereas when the vortices are mobile, this field distribution is smeared by the vortex motion. (Note that muons do not move with vortices.) The same applies to the minimum field except that it is shifted upwards. Thus $\langle\Delta B^2\rangle$ must become smaller when vortices move.

A more elaborate analysis has shown, in fact, that even the temperature dependence of $\langle\Delta B^2\rangle$ may be altered[7] depending on how much motion is allowed. Instead of a standard $1/\lambda^2$ type temperature dependence (negative curvature with temperature), it may exhibit positive curvature.

For the vortex motion to manifest itself in μSR, it is necessary for a vortex to move over [illegible] vibrate [illegible] a significant fraction of the inter-vortex distances within a muon's lifetime. (The fraction needed is about 1/4 at T_c, and the rms distance from the original position having $T^{1/2}$-like temperature dependence, consistent with either diffusive or vibrating motion.) We can roughly estimate from the resistivity measurement of Ref. 1 if this condition is met. Consider the typical speed at which the vortices (or vortex discs, in the case of layered superconductors) move in these experiments: 1 cm/s at $10^5 \sim 10^6$ A/m^2 at $T \approx 80$ K for $Bi_2Sr_2CaCu_2O_8$. From this, and assuming that vortices are independent of each other and that Einstein's relation holds, we can estimate the diffusion constant for this material. We find it to be about 10^9 Å^2/μs, a number too large to be reasonable. Clearly, a correction is necessary to account for the more microscopic theory of energy dissipation associated with vortex motion. However, the fact that this number turns out to be so large is an indication that the vortices are very mobile in $Bi_2Sr_2CaCu_2O_8$, and that this motion can be seen in μSR experiment.

The actual experiment on $Bi_2Sr_2CaCu_2O_8$ has recently shown[6] that $\langle\Delta B^2\rangle$ indeed shows *positive* curvature with temperature at $H = 3$ and 4kG. We have compared these data with our theory, and obtained a satisfactory agreement if we assume that the vortices move about 250 Å within a muon lifetime at T_c.[7] The overall scale of $\langle\Delta B^2\rangle$ is strongly influenced by the amount of vortex disorder present in the sample as it is cooled down to the lowest possible temperature.[5] Therefore, the penetration length λ is difficult to estimate for these materials. Nevertheless, we estimate this to be about 3000 Å.[7]

Our study also showed that the third moment of the field distribution, $\langle\Delta B^3\rangle$, is just as important in studying the low temperature vortex dynamics.[illegible] It can be shown that the third moment, which is a measure of the asymmetry of the field distribution, is small when vortices are mobile. This is simply due to the fact that no muon can measure the core magnetic field, and that the field distribution no longer has a long high magnetic field tail associated with the core. Such a tail is only observable when the vortex motion is small. Thus, by looking at $\langle\Delta B^3\rangle$ at different temperatures, one can locate the "freezing" temperature of vortices. We find this to be about 40 K for $Bi_2Sr_2CaCu_2O_8$, below which $\langle\Delta B^3\rangle$ shows a rapid increase from ≈ 0 with lowering temperature.[6] It seems to indicate that it is not a first order phase transition (ergo, not melting), and it is found to be consistent with a rapid crossover of the thermal activation picture as well as a second order or Kosterlitz-Thouless transition. If the thermal activation model applies, this "freezing" temperature must be dependent on the time and length scales involved in the experiment. (for μSR, they are 2.2 μs and a few hundred Å).

Finally, since the field distribution may show a temperature dependent asymmetry as mentioned above, it is clearly not sufficient to simply fit a gaussian decay to a μSR signal. It, in fact, does not even give a good fit for $Bi_2Sr_2CaCu_2O_8$. We suspect that this will be the case for any mixed state superconductors with high critical temperature and large anisotropy, and we also believe that it is essential to check if the quality of the fit is satisfactory before $\langle\Delta B^2\rangle$ etc. are computed. Otherwise, the result would be inaccurate and misleading.

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